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Manjit K. Misra

*Iowa State University*, [mkmisra@iastate.edu](mailto:mkmisra@iastate.edu)

D. B. Brooker

*Iowa State University*

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# Thin-Layer Drying and Rewetting Equations for Shelled Yellow Corn

M. K. Misra, D. B. Brooker

ASSOC.  
MEMBER  
ASAE

FELLOW  
ASAE

## ABSTRACT

**T**HIN-LAYER drying and rewetting data for shelled yellow corn have been compiled from all available sources. A thin-layer drying equation was developed using these data with air temperature, air humidity, air velocity and corn initial moisture content as the independent variables. A thin-layer rewetting equation was also developed. The equation contains air temperature, air humidity and corn initial moisture content as the independent variables.

## INTRODUCTION

Simulation models that predict the drying behavior of a deep bed of grain usually are based on the assumption that the deep bed is composed of and dries as a series of thin-layers. Therefore, the validity of deep bed models is directly dependent on how well the thin-layer drying and rewetting equation used in the model describe the thin-layer process.

A number of researchers (Chittenden, 1961; Chu, 1966; Muh, 1974; Page, 1949; Rodriguez-Arias, 1956; Rugamayo, 1978; Sabbah, 1968; Thompson, 1967; Troeger, 1967; del-Giudice, 1959) have developed thin layer drying or rewetting equations for shelled corn from experimental data obtained in selected ranges of corn moistures and air conditions. Each investigator has developed an equation from his own data with conditions of his interest. Table 1 is a compilation of the range of variables used by these researchers in developing equations. Several of the thin-layer equations may have to be incorporated in a deep bed model to adequately simulate drying or rewetting under all corn moistures and air conditions encountered.

At least 8 thin-layer drying equations are available in the range of 36°F to 160°F (2.2°C to 71.1°C). These equations vary widely in nature. Equations by Chittenden (1961) and Chu (1966) use concepts of pseudo initial moisture content and dynamic equilibrium moisture content. Page's (1949) equation uses constants which are not expressed as functions of independent variables. The equation by Rodriguez-Arias (1956) contains different values of drying parameters for each stage of drying. The ranges of temperatures for the equations by Rugamayo (1978) and Sabbah (1968) are rather narrow. A set of complicated equations by Troeger (1967) is the only model that includes an airflow term. Chu's (1966) equa-

tion is the only one that directly takes account of the effect of initial moisture content. Thus, confusion arises as to which equation(s) to use in simulation models for various corn moistures and air conditions.

Table 1 shows that only one equation (del-Giudice, 1959) is available to describe the thin-layer rewetting process. Rewetting does occur in a drying bed and should be considered in deep bed drying models.

## OBJECTIVES

The specific objectives of this research were:

1 To conduct thin-layer drying and rewetting tests to obtain experimental data for shelled corn using air temperatures and humidities for which data are limited or non-existent.

2 To compile all available data on thin-layer drying and rewetting in the temperature range of 36°F to 160°F (2.2°C to 71.1°C).

3 To develop a single thin-layer drying equation using all data in the temperature range of 36°F to 160°F (2.2°C to 71.1°C).

4 To develop a thin-layer rewetting equation using all data at hand.

## EQUIPMENT AND PROCEDURE

An apparatus which permitted the moisture change to be monitored continuously and automatically was used to conduct the thin-layer tests. The details of the apparatus and procedure are presented in a paper by Misra and Brooker (1978). In all, 23 thin-layer drying and 6 rewetting tests were conducted. These data supplemented the data collected from other sources.

## COMPILATION OF DATA

This study represents the first comprehensive attempt to survey and compile all the thin-layer data for shelled

TABLE 1. RANGE OF VARIABLES USED IN THIN-LAYER DRYING AND REWETTING EQUATIONS

Source	Temperature		Relative humidity, %	Airflow		Initial moisture content, % db
	Deg. F	Deg. C		ft/min	m/s	
Chittenden (1961)	70-100	21.1- 37.7	10 -83	459	2.33	19 -60.1
Chu (1966)	120-160	48.9- 71.1	10.5 -70.2	459	2.33	25 -35
Muh (1974)	80-220	26.7-104.4	20 -60	5	0.025	—
Page (1949)	60- 90	15.6- 32.2	34.8 -70.7	61-120	0.31-0.61	21.4 -36.2
Rodriguez-Arias (1956)	40-140	4.4- 60	11.1 -96.3	—	—	17.48-44.5
Rugamayo (1978)	40- 70	4.4- 21.1	40 -60	5	0.025	26.99-28.3
Sabbah (1968)	36- 70	2.2- 21.1	22 -80	168	0.853	38.7 -40.61
Thompson (1967)	140-300	60 -148.9	—	20- 60	0.1 -0.305	23.46-49.2
Troeger (1967)	90-160	32.2- 71.1	0.11-83.2	20-160	0.1 -0.813	19.83-47.9
del-Giudice (1959)	60-105	15.6- 40.6	60 -100	10	0.051	—

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The authors are: M. K. MISRA, Asst. Professor, Seed Science Center, Iowa State University, Ames; and D. B. BROOKER, Professor, University of Missouri-Columbia, Columbia.

TABLE 2. DETAILS OF COMPILED THIN-LAYER DRYING DATA

Source	No. of observations	Temp (T), °C		Relative Humidity (H), %		Airflow (V), m/s		Initial moisture content, M <sub>o</sub> % d.b.		Time, (t) h	Moisture content, M, % d.b.	
		Min. value	Max. value	Min. value	Max. value	Min. value	Max. value	Min. value	Max. value	Max. value	Min. value	Max. value
Chittenden (1961)	3514	21.1	37.7	10.0	83.0	2.33	2.33	19.0	60.10	32.0	10.58	60.10
Chu (1966)	6397	48.9	71.1	10.5	70.2	2.33	2.33	22.63	37.46	27.0	5.38	37.46
Misra (1978)	579	10.0	43.3	30.0	90.0	0.076	0.38	28.36	30.44	30.0	10.81	30.44
Muh (1974)	560	26.7	60.0	20.0	60.0	0.025	0.025	—	—	19.5	0.0031*	1.0*
Page (1949)	232	15.6	32.2	34.8	70.7	0.31	0.61	21.40	36.20	263.0	9.50	36.20
Rodriguez-Arias (1956)	13	37.7	37.7	43.4	43.4	—	—	18.35	18.35	7.0	14.68	18.36
Rugamayo (1978)	253	4.4	21.1	40.0	60.0	0.025	0.025	26.99	28.31	47.0	15.54	28.31
Sabbah (1968)	109	2.2	21.1	22.0	80.0	0.853	0.853	38.70	40.61	221.0	8.93	40.61
Troeger (1967)	5101	32.2	102.2	0.1	83.2	0.1	0.813	19.83	47.99	657.8	0.02	48.70

\*Moisture ratio (MR)

corn available in the drying air temperature ranges of 36 to 160°F (2.2°C to 71.1°C).

Data were collected via personal communications and from copies of theses obtained from University-Microfilms International. Thin-layer drying data were collected from 9 different sources (Chittenden, 1961; Chu, 1966; Misra, 1978; Muh, 1974; Page, 1949; Rodriguez-Arias, 1956; Rugamayo, 1978; Sabbah, 1968; Troeger, 1967) including the data obtained from the tests conducted during this study. In all, data for 813 tests are compiled for thin-layer drying. These consist of 16,758 observations. There are 14 tests compiled for rewetting and they consist of 401 observations. The data for rewetting came from 3 sources (Chittenden, 1961; Misra, 1978; Rugamayo, 1978). The del-Giudice thesis (1959) presents curves, but does not give data in tabular form.

The thin-layer data were coded, punched on computer cards and are stored on a magnetic tape at the Computer Center at the University of Missouri-Columbia. The code used for each test gives the values of all the independent variables and the source of that test. The entire compiled data is presented in the appendix of the thesis by Misra (1978). The essential details and the range of various variables for the compiled thin-layer drying data are presented in Table 2. Similar statistics are given in Table 3 for the compiled thin-layer rewetting data.

### DATA SELECTION

Not all of the compiled data were used. The observations that fell into the following categories were not in-

cluded in the analysis of thin-layer drying data.

1 The results of the tests that were run at temperatures above 160°F (71.1°C).

2 The results of the tests that were run at humidities below 1 percent.

3 The results of the tests for which any test variable was not reported.

4 The experimental observations where corn moisture was below the calculated value of M<sub>e</sub>, because they required the computer to calculate the logarithm of a negative number. M<sub>e</sub> was determined from the "De Boer" equation developed by Bakker-Arkema, et al. (1974). The tests conducted at 90 percent relative humidity consisted of many such observations.

A total of 774 tests were included in the analysis of thin-layer drying. These tests consisted of 15,353 observations.

Some of the data compiled for thin-layer rewetting were not used in developing the thin-layer rewetting model. The results of three tests by Chittenden (1961) were not included due to the very small amount of rewetting that occurred during these tests. Less than 1 percent rewetting occurred in the first test, less than 2 percent in the second and less than 3 percent in the third. Thus, a total of 11 tests were included in the analysis for thin-layer rewetting. These tests consisted of 293 observations.

### ANALYSIS

The compiled combined data were voluminous and

TABLE 3. DETAILS OF COMPILED THIN-LAYER REWETTING DATA

Source	No. of observations	Temp (T), °C		Relative Humidity (H), %		Airflow (V), m/s		Initial moisture content, M <sub>o</sub> % d.b.		Time, (t) h	Moisture content, M, % d.b.	
		Min. value	Max. value	Min. value	Max. value	Min. value	Max. value	Min. value	Max. value	Max. value	Min. value	Max. value
Chittenden (1961)	108	21.1	21.1	75.0	83.0	2.33	2.33	19.09	21.72	30.0	19.9	22.94
Misra (1978)	143	10.0	43.3	90.0	90.0	0.076	0.38	7.75	9.65	30.0	7.75	18.57
Rugamayo (1978)	150	10.0	21.1	100.0	100.0	0.025	0.025	15.54	24.45	55.0	15.54	30.13

heterogeneous. Hence, it was necessary to conduct a preliminary analysis on a small sub-set of the data. A portion of the data collected from actual tests run during this study was selected for this purpose. The preliminary analysis identified the most promising model to be,

$$MR = \exp(-Kt^N) \quad [1]$$

or

$$\ln(-\ln(MR)) = \ln(K) + N \ln(t) \quad [2]$$

The final analysis then, using the combined data, was to find suitable expressions for  $K$  and  $N$  as functions of test variables. The variables included in the analysis were:  $T$ ,  $T^2$ ,  $\ln(T)$ ,  $H$ ,  $H^2$ ,  $\ln(H)$ ,  $V$ ,  $V^2$ ,  $\ln(V)$ ,  $M_o$ ,  $M_o^2$  and  $\ln(M_o)$ . An exponential function for  $K$  and a polynomial function for  $N$  were found to give the best results among all the expressions considered.

$$K = \exp [K_0 + K_1 T + K_2 T^2 + K_3 \ln(T) + K_4 H + K_5 H^2 + K_6 \ln(H) + K_7 V + K_8 V^2 + K_9 \ln V + K_{10} M_o + K_{11} (M_o)^2 + K_{12} \ln(M_o)] \quad [3]$$

$$N = N_0 + N_1 T + N_2 T^2 + N_3 \ln(T) + \dots N_{12} \ln(M_o) \quad [4]$$

Substituting the expressions for  $K$  and  $N$  in equation 2,

$$\begin{aligned} \ln [-\ln(MR)] = & K_0 + K_1 T + K_2 T^2 + K_3 \ln(T) + K_4 H + \\ & K_5 H^2 + K_6 \ln(H) + K_7 V + K_8 V^2 + K_9 \ln(V) + K_{10} M_o + \\ & K_{11} M_o^2 + K_{12} \ln(M_o) + \ln(t) [N_0 + N_1 T + N_2 T^2 + N_3 \ln(T) + \\ & \dots + N_{12} \ln(M_o)] \quad [5] \end{aligned}$$

Equation [5] is a particular case of a general linear regression model. Therefore, the coefficients  $K_0$  to  $K_{12}$  and  $N_0$  to  $N_{12}$  can be determined.

The regression model in equation [5] contains a lengthy list of independent variables. Such a model is difficult and expensive to analyze. Further, the independent variables that are intercorrelated may add little to the predictive power of the model. Therefore, it is necessary to shorten the list so as to obtain the "best" set of independent variables.

Many search procedures are available to find the "best" set. In this analysis, the RSQUARE procedure of SAS (Statistical Analysis System) was used. This procedure performed regressions of the response variable on sub-sets of the independent variables. If  $p$  variables are

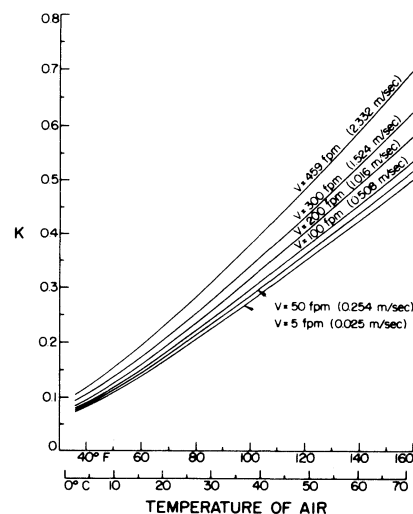


FIG. 1 The drying parameter  $K$  as a function of air temperature and velocity.

specified, RSQUARE evaluated  $R^2$  statistics for  $2^p$  linear models. A  $p$  number of these models have only one independent variable,  $p(p-1)/2!$  of the models have two independent variables and so forth. The procedure then identified the model that produced the highest  $R^2$  value among the models containing the same number of independent variables (same number of terms). The final model did not contain an independent variable if such a variable produced only a marginal improvement in  $R^2$ .

The equation used to calculate  $M_e$  was developed by Bakker-Arkema, et al. (1974) from Rodriguez-Arias (1956) data and was arbitrarily selected for this study. The calculated values of equilibrium moisture content from the equation in some cases deviate as much as 2 percent when compared to actual data by Rodriguez-Arias. In most tests, the drying curve tended towards the values of calculated  $M_e$ .

## RESULTS

### Thin-layer drying

The following thin-layer drying equation was developed using all selected experimental data:

$$M = (M_o - M_e) \exp(-Kt^N) + M_e \quad [6]$$

$$K = \exp(-7.1735 + 1.2793 \ln(1.8T + 32) + 0.1378V) \text{ SI units}$$

$$K = \exp(-7.1735 + 1.2793 \ln(T) + 0.0007V) \text{ English units}$$

$$N = 0.0811 \ln(H) + 0.0078 M_o$$

TABLE 4. CALCULATED STATISTICS FOR INDIVIDUAL DATA SETS USING EQUATION [6]

Source	No. of tests	No. of observations	USS	CSS	SSE	$R^2$
Chittenden (1961)	94	3514	1928428.0	193807.2	5317.4	0.973
Chu (1966)	433	6397	2044736.0	223651.3	9899.8	0.956
Misra (1978)	17	429	185667.2	11767.1	967.3	0.918
Page (1949)	10	205	69937.3	6166.6	971.3	0.842
Rugamayo (1978)	5	167	78325.9	1826.9	364.3	0.801
Sabbah (1968)	7	105	71976.3	7436.0	800.0	0.892
Troeger (1967)	208	4536	2063221.0	487324.5	14712.1	0.970
Combined data	774	15353	6442355.7	1002858.0	33032.2	0.967

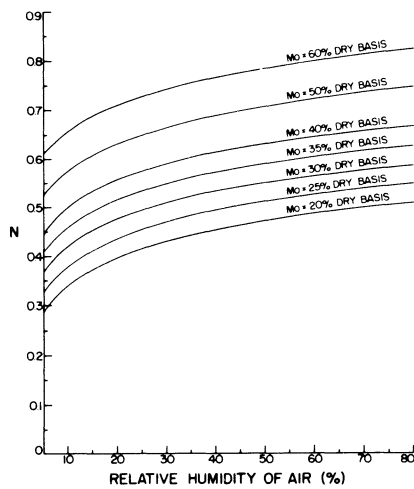


FIG. 2 The drying parameter  $N$  as a function of air relative humidity and the original corn moisture content.

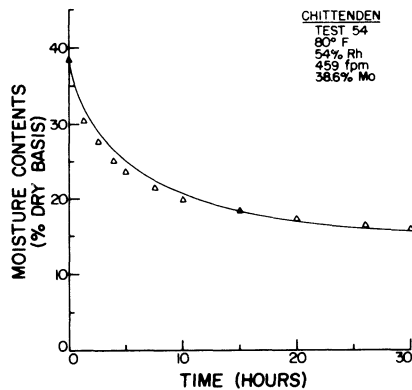


FIG. 5

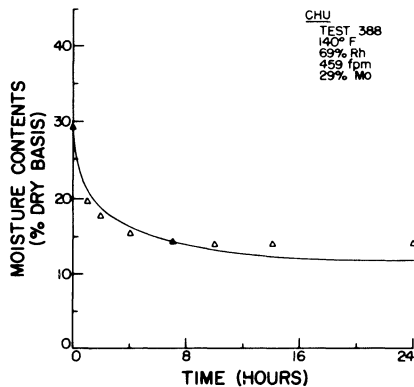


FIG. 6

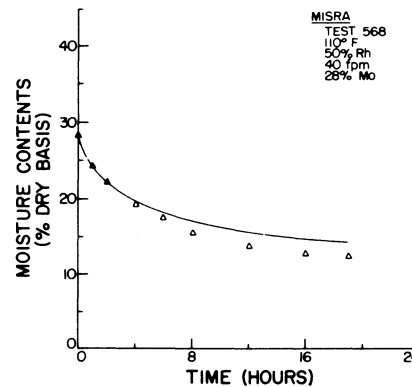


FIG. 7

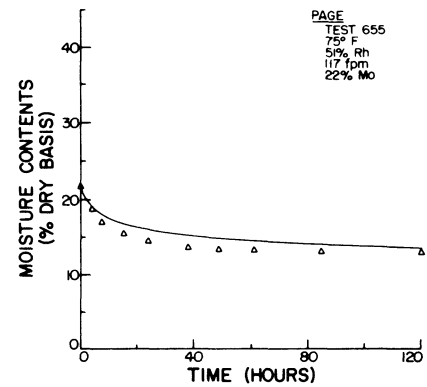


FIG. 8

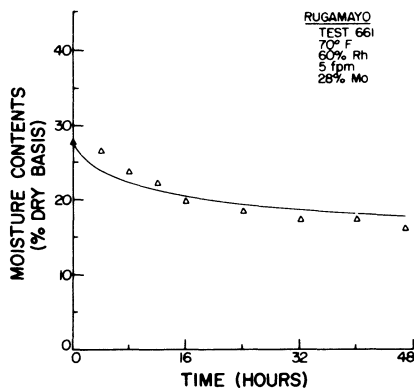


FIG. 9

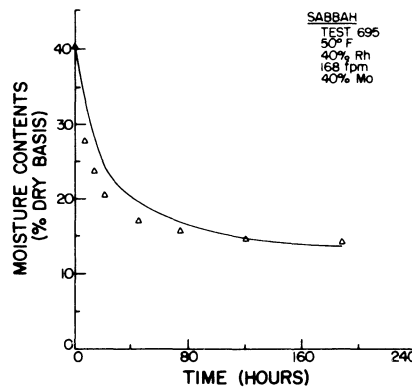


FIG. 10

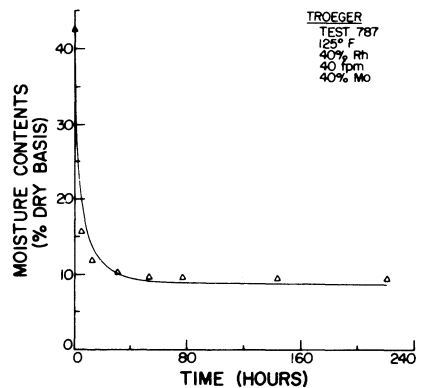


FIG. 11

FIG. 5 to 11 Theoretical drying curves plotted against data points for "representative" data sets.

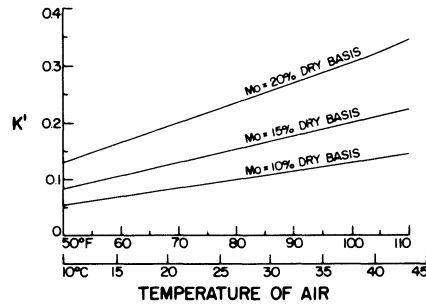


FIG. 3 The rewetting parameter  $K'$  as a function of air temperature and original corn moisture content.

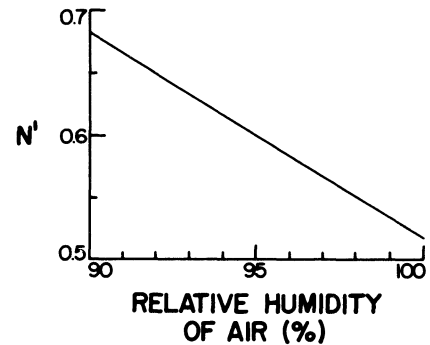


FIG. 4 The rewetting parameter  $N'$  as a function of air relative humidity.

The ranges of independent variables used to develop the above equation are:

Drying air temperature: 36 to 160°F (2.2°C to 71.1°C)

Drying air relative humidity: 3 to 83 percent

Drying air velocity — 5 to 459 ft/min (.025 to 2.33 m/s)

Corn initial moisture — 18 to 60 percent (dry basis)

The  $R^2$  value for the above thin-layer drying equation for all data was 0.967. Statistics were also calculated for each individual data-set from the various sources and are presented in Table 4.

Fig. 1 shows the variation of the thin-layer drying parameter  $K$  with respect to air temperature for different values of air velocity. In Fig. 2, the parameter  $N$  is plotted with respect to air relative humidity for different values of corn initial moisture content.

#### Thin layer rewetting

The following thin-layer rewetting equation was

developed using all selected experimental data.

$$M = (M_o - M_e) \exp(-K' t^{N'}) + M_e \dots \dots \dots [7]$$

$$K' = \exp(-8.5122 + 1.2178 \ln(1.8T + 32) + 0.0864 M_o) \text{ SI units}$$

$$K' = \exp(-8.5122 + 1.2178 \ln(T) + 0.0864 M_o) \text{ English units}$$

$$N' = 2.1876 - 0.0167H$$

The ranges of independent variables used to develop the above equation are:

air temperature: 50 to 110°F (10 to 43.3°C)

air humidity: 90 to 100 percent

air velocity: 5 to 75 ft/min (0.25 to 0.382 m/s)

corn initial moisture content: 7.75 to 24.45 percent (dry basis)

The R<sup>2</sup> value for equation [7], using all data, was 0.991.

Fig. 3 shows the variation of K' with respect to air temperature for different values of corn initial moisture content. Fig. 4 is a plot of N' with respect to the relative humidity of the drying air. The plot for N' is made assuming a straight line relationship between 90 percent and 100 percent relative humidity which are the two levels of humidities used in the analyses.

## DISCUSSION

Fig. 5 through 19 are illustrations of how well a curve of calculated values fit data of some of the drying tests. Fig. 5 through 11 are "representative" plots of data from the seven sources. They show neither the "best" or the

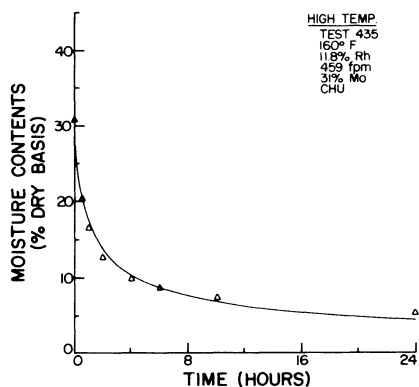


FIG. 12

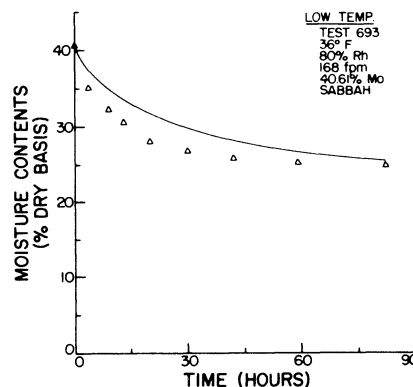


FIG. 13

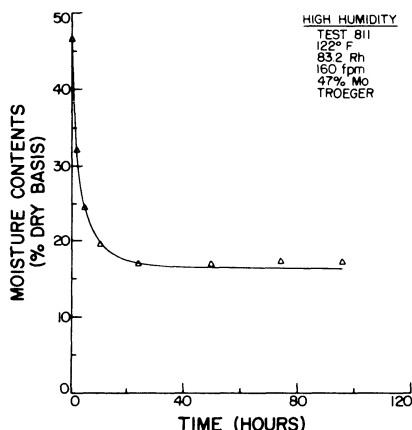


FIG. 14

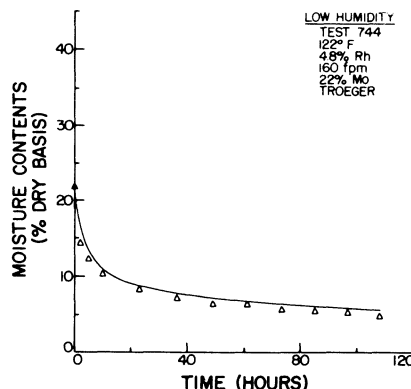


FIG. 15

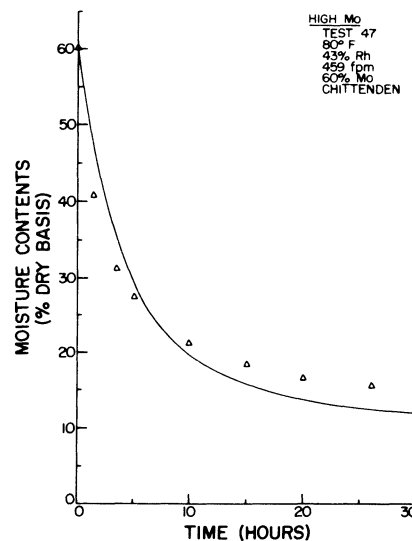


FIG. 16

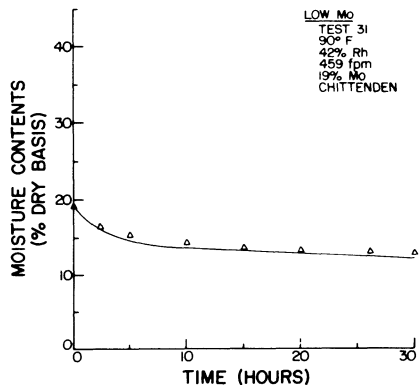


FIG. 17

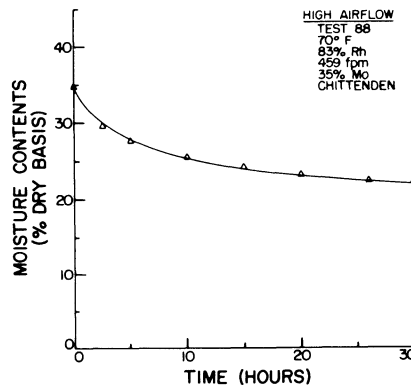


FIG. 18

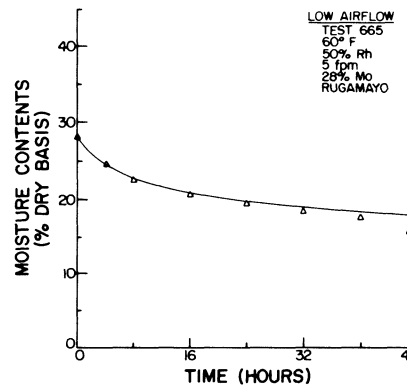


FIG. 19

FIG. 12 to 19 Theoretical drying curves plotted against data points for extreme conditions of the independent variables.

"worst" fit. What is shown is a typical test from each source that had an  $R^2$  value nearest to the  $R^2$  value of the entire data set. Fig. 12 through 19 show plots for extreme conditions of the independent variables, ie. for tests that were conducted with high and low values of temperature, relative humidity, initial moisture and airflow.

The fact that the curves fit some test data better than others is not surprising when the heterogeneous nature of the data is considered. There were differences in procedure used to obtain data. For example, Troeger (1967) placed the grain samples in the dryer directly from storage at 35°F (1.7°C). Other researchers allowed the grain samples to warm at room temperature. Some researchers weighed the sample at periodic intervals and others used a continuous recording apparatus. The datasets by a number of researchers included observations for a few hours, whereas in other tests, such as Troeger (1967), observations up to 27 days were reported. The design and the dimensions of the thin-layer dryer also varied. The initial preparations of the sample (grading, use of naturally moistened or rewetted sample) were not

uniform.

If  $t^N$  is treated as a new (modified) time variable, then  $K$  is the proportionality factor relating the drying rate  $dm/d(t^N)$  to the available moisture  $(M - M_e)$ .  $N$  can be considered as the modification factor for the time variable that reflects the extent of internal resistance to drying in the grain for a particular set of external conditions.  $N$  may account for the moisture gradients established in the grain during drying or the effect of the history of drying on drying rate. In other words,  $K$  can be thought of as representing the effect of external conditions and  $N$  may represent the effect of internal changes in the grain due to the manner in which these external conditions were imposed. Similar logic also applies to the thin-layer rewetting parameters.

Fig. 20 to 26 show the plots for the experimental and calculated rewetting data. The equation developed to describe the thin-layer rewetting produces a satisfactory fit of the experimental data.

The comparison between the experimental and predicted values of moisture content (percent dry basis) for each test, drying and rewetting, is presented in tabular form in the appendix of a thesis by Misra (1978).

## CONCLUSIONS

1 Thin-layer drying and rewetting equations (equations [6] and [7] were developed using data from all known available sources. The developed equations are simple and contain pertinent independent variables.

2 The thin-layer drying equation fits the data of 774 tests with an  $R^2$  value of 0.967.

3 The thin-layer rewetting equation fits the data of 11 tests with an  $R^2$  value of 0.991.

4 Among all the independent variables considered, the drying air temperature and the velocity of air most

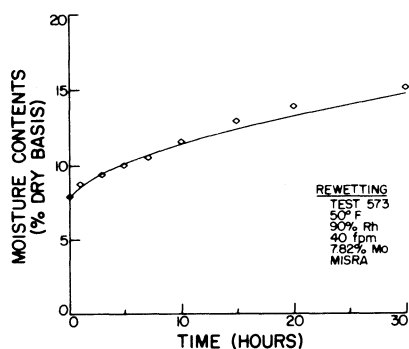


FIG. 20

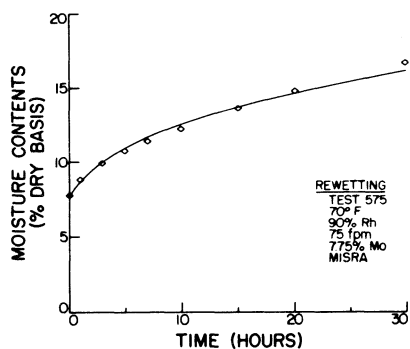


FIG. 21

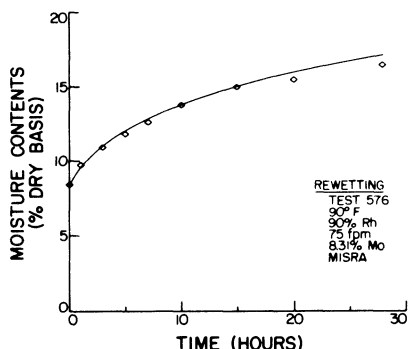


FIG. 22

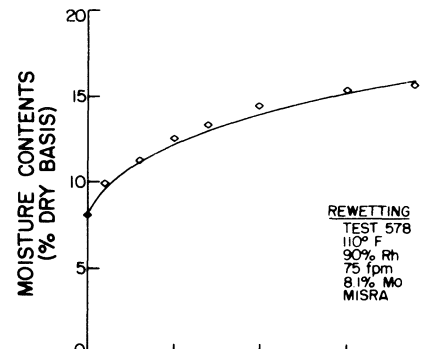


FIG. 23

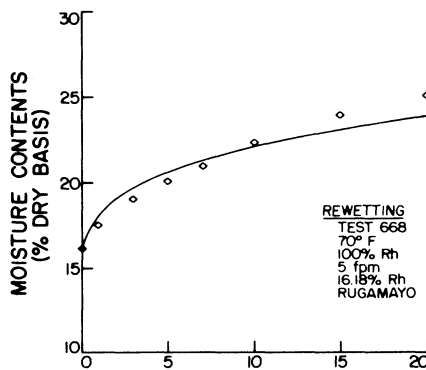


FIG. 24

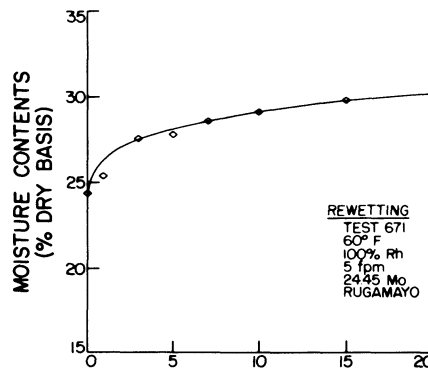


FIG. 25

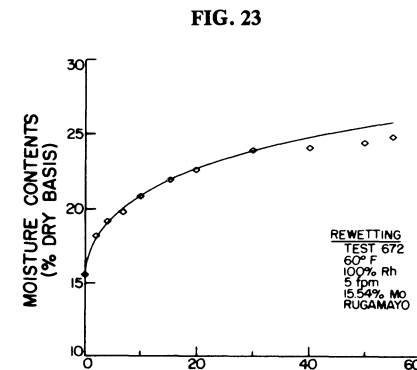


FIG. 26

FIG. 20 to 26 Theoretical rewetting curves plotted against data points.

significantly affect the parameter K in the thin-layer drying equation. The parameter N in the equation was found to be a function of the relative humidity of air and corn initial moisture content.

5 Among all the independent variables considered, the air temperature and the initial moisture content of corn most significantly affect the parameter K' in the thin-layer rewetting equation. The parameter N' in the equation was found to be a function of the relative humidity of air.

6 The heterogeneous nature of the data compiled suggests that a standard method be adopted by ASAE to conduct thin-layer tests.

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## LIST OF SYMBOLS

t	time (h)
H	relative humidity of air (percent)
K	parameter in thin-layer drying equation
K'	parameter in thin-layer rewetting equation
M	moisture content dry basis (percent)
M <sub>e</sub>	equilibrium moisture content dry basis (percent)
M <sub>o</sub>	initial moisture content dry basis (percent)
N	parameter in thin-layer drying equation
N'	parameter in thin-layer rewetting equation
T	temperature in air (°F) or (°C)
V	velocity of air (ft/min or m/s)

## ABBREVIATIONS

MR	moisture ratio, $(M - M_e)/(M_o - M_e)$
R <sup>2</sup>	coefficient of determination, $(CSS-SSE)/(CSS)$
CSS	corrected sum of squares for the moisture content (percent dry basis)
SEE	sum of squares of residuals
USS	uncorrected sum of squares for the moisture content (percent dry basis)